TITLE: Flaw Tolerant Safe-Life Methodology

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ABSTRACT

Conventional safe-life methodology has been in general use in the helicopter industry for more than 40 years to substantiate fatigue-loaded dynamic components. However, it is seen to need improvement. One improvement is to reduce its sensitivity to the strength-reducing effects of flaws and defects that may occur in manufacturing and service use. Damage Tolerance methodology provides a means to accomplish this improvement but it is currently difficult to economically apply it to every fatigue mode on every component. Flaw Tolerant methodology is an available equal-choice option to Damage Tolerance for Transport Category civil rotorcraft, and it is offered here as a practical improvement to conventional safe life for military applications as well. Flaw Tolerance, which is based on the characteristics of initiation of cracks from flaws, is described and illustrated by means of examples of successful applications to helicopter components.

INTRODUCTION

This paper provides a description and examples of successful applications of Flaw Tolerance. The method is currently available for Transport Category civil rotorcraft via FAR 29.571, References 1 and 2. Although the method is applicable to composites, this discussion will be limited to metals applications. Also, the discussion focuses on fatigue-substantiated components in the rotor, drivetrain, and control systems, although there may be opportunities to apply Flaw Tolerance to airframe structure as well.

Definition of terms is an immediate difficulty in this field. Different sources may use conflicting definitions of common terms. This is due to the simultaneous evolution of fatigue substantiation methodologies in related but independent endeavors over the last 40 years. For example, the term "Damage Tolerance" is deliberately avoided in the FAR 29.571 advisory material, Reference 2, even though most readers think that this is precisely what is being discussed. This paper will use the definitions proposed as a joint position of the AIA/AECMA helicopter companies in Reference 3. The term Damage Tolerance will be used to describe the evaluation of crack growth characteristics, including the conclusion of no growth of cracks. The term Flaw Tolerance (also called Flaw Tolerant Safe Life or Enhanced Safe Life) will be used to describe the evaluation of crack initiation characteristics from flaws. Using these definitions for the methodology described in FAR 29.571 would result in saying that the FAA's "Fatigue Tolerance" requirement can be met equally by either a Damage Tolerance or a Flaw Tolerance approach.

Flaw Tolerance is being presented here because it is a method that is not well known and has not been widely used, or at least was not called Flaw Tolerance when it was used. However, it can provide the same benefits in helicopter fatigue applications as Damage Tolerance, while avoiding some of the issues which can make Damage Tolerance very difficult to apply in practice to every helicopter dynamic component. Flaw Tolerance could also be regarded as a useful and positive interim approach to improving helicopter fatigue substantiations while the Damage Tolerance Methodology matures and develops to a point where it can be used in practice more universally.

Finally, it is noted here that Flaw Tolerance is not used by all manufacturers, nor is it the first choice of all certifying agencies, however, all of the AIA/AECMA helicopter manufacturers have agreed that it should be retained as an available equal-choice alternate method for civil applications (Reference 3).

BACKGROUND

A conventional safe-life approach has been the most frequent choice of all helicopter manufacturers since the 1950's to substantiate fatigue-loaded flight-critical dynamic components in both civil and military applications. This approach requires knowledge of three elements for each substantiated component: 1) S-N curves representing the crack initiation fatigue strength for each mode of failure; 2) Loads for each flight regime in the mission spectrum; and 3) Rate of occurrence in service (usage) for each of these regimes. The strength, loads, and usage elements are combined, by a linear cumulative damage rule (Miner's Rule), to calculate a safe retirement time. The conservative margins included in each of the three elements produce a very high level of reliability in the result. However, in spite of its overall success in helicopter applications, this method does not account for any component strength that deviates from the strength distribution assumption made during the fatigue substantiation process. Historically, many of these strength-reducing problems derive from flaws and defects generated as a result of manufacturing, maintenance, and service use.

The need to improve civil helicopter structural tolerance to flaws and defects was recognized by the Federal Aviation

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Administration in the U.S. in the 1980's. Damage Tolerance methodology was also being applied at that time with considerable success to fixed wing aircraft in both military and civil applications. These ideas represented a significant and important change in direction for the civil helicopter community. The requirements were promulgated in Amendment 28 to Paragraph 29.571 of the Federal Aviation Regulations, Reference 1, and Advisory Circular 29-2A Amendment 1, Reference 2, applicable to Transport Category helicopters (over 2700 kg gross weight). These requirements use the words "fatigue evaluation of structure including flaw tolerance" and permit either a "Fail-Safe Evaluation" (residual strength after flaw growth) or a "Flaw Tolerant Safe-Life Evaluation".

Although confusing in terms, the new rule required the application of either Damage Tolerance or Flaw Tolerance to all Primary Structural Elements unless it was shown to be impractical, in which case a conventional safe-life approach could be used. Flaw Tolerance was included to provide the manufacturers a means of accounting for flaws and defects using basic safe-life methodology that was highly developed and whose shortcomings were very well understood. Damage Tolerance had already achieved a high level of success in transport aircraft, and had seen some successful applications in the helicopter world as well. However, it was seen as a major risk to commit to applying it to all new helicopter dynamic components, given the high cycle rate of fatigue loading and the possibility of frequent difficult inspections.

There has also been some direct experience with Flaw Tolerance, although it may have been called something else when we used it. Sikorsky conducted a fatigue program for the U.S. Navy in 1986 where the effects of known strength-reducing conditions on CH-53A/D dynamic components were evaluated with a coupon program and safe-life methods. In addition, Sikorsky has employed a Flaw Tolerant approach in the resolution of several field problems, and in the original substantiation of some military components. Examples of all of these are found later in this paper. A technical paper, Reference 4, with authors from 3 U.S. helicopter companies, promoted consideration of "degraded modes" in safe-life substantiations in 1988.

Only one completely new civil helicopter project has applied for certification under the new rule - the Sikorsky S-92 "Helibus", Figure 1. All options permitted by the rule were evaluated and used. Flaw Tolerance was the method most frequently chosen for the initial substantiation of the dynamic components. As the substantiation progresses and strength and loads data are obtained, this choice will be reevaluated. The S-92 is currently in the early stages of its flight test development, and its application of Flaw Tolerance methodology can be examined, as described in an example later in this paper.

Figure 1. Sikorsky S-92 "Helibus".

THE FLAW TOLERANCE METHOD

The following description of the Flaw Tolerant method is extracted from Reference 3. It meets the requirements of FAR 29.571, and includes provisions to derive inspection intervals for flaws, which is not required by some interpretations of FAR 29.571 and its advisory material.

Just as with Damage Tolerance, Flaw Tolerance is intended to assure that should serious corrosion, accidental damage, or manufacturing/maintenance flaws occur within the specified retirement time and/or inspection intervals of the component, the structure will not fail.

Basics of the Flaw Tolerant Method

The Flaw Tolerant method provides component management requirements based on the assumption of the existence of flaws in the component's critical areas. Two sizes of flaws are considered:

1) "Barely Detectable Flaws" are used to conservatively represent the largest probable undetectable manufacturing or service-related flaws.

2) "Clearly Detectable Flaws" are the largest probable manufacturing or service-related flaws that would not normally be detected in a routine visual inspection such as a pre-flight or weekly.

The approach to Flaw Tolerant design of Principal Structural Elements depends on the type of structure. The approach for single load path structure has two requirements:

1) A barely detectable flaw will not initiate a propagating crack within the retirement time of the component; and

2) A clearly detectable flaw will not initiate a propagating crack within an inspection interval, inspecting for the presence of the flaw.

The approach for multiple load path or fail-safe structure also has two requirements:

1) A barely detectable flaw will not initiate a propagating crack within the retirement time of the component; and

2) A barely detectable flaw in a second load path, after the first load path failure, will not initiate a propagating crack within an inspection interval, inspecting for first load path failure.

Determining Flaw Types and Sizes

Flaw types and sizes to be imposed on each component being substantiated by Flaw Tolerance are defined, and are submitted with accompanying rationale to the certifying agency for approval. The first element of this process is a systematic evaluation of the types and sizes of flaws to be considered for each component. The types of flaws considered should include nicks, dents, scratches, inclusions, corrosion, fretting, wear, and loss of mechanical joint preload or bolt torque.

The systematic evaluation should include a compilation of historical experience with similar parts and materials, including field service reports, overhaul and repair reports, metallurgical evaluations, manufacturing records, and accident/incident investigations. The design, manufacturing, maintenance, and overhaul practices and processes that could result in errors or defects should also be evaluated. Planned inspection methods and practices also define what size and locations of flaws are likely to be detectable. A coupon program is valuable in indicating the strength-reducing effects of various types of flaws, S-N curve shape and statistical scatter for flawed parts, and, if needed, determination of "equivalent" flaw types and sizes that may be used on full-scale test specimens. This is illustrated in Figure 2.

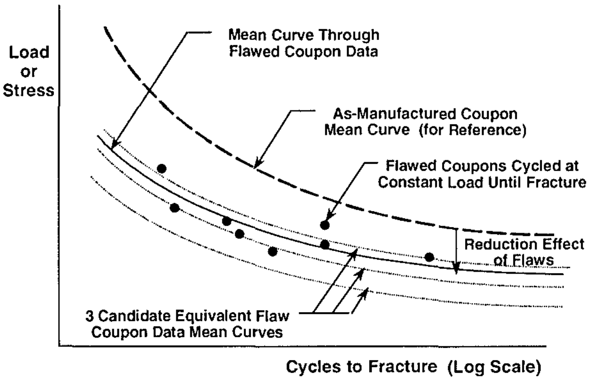

Figure 2. Coupon Evaluation of Flaws.

Consideration should also be given to factors that reduce the chance of error, such as "frozen processes", Flight Critical Parts programs, material selection to avoid inclusions and defects, and procedures to reduce manufacturing errors. Another possibility is to limit the flaws considered if the design includes surface treatments that protect against environmental and/or accidental mechanical damage. In addition, it may be appropriate to show by means of a joint probability analysis that some flaws may be eliminated from consideration because they have an extremely remote chance of a critical occurrence. This analysis combines the distribution of likely flaw sizes, the criticality of location and orientation, and the likelihood of being missed in an inspection.

If this evaluation determines that a possible flaw is a true crack, the Flaw Tolerance method may not be valid. Cracks of this sort could be related to manufacturing errors in plating or surface treatments, heat treatment, or cold working. For these specific defects, an analytical evaluation should be conducted, using fracture mechanics methods, to verify that these cracks will not grow under the expected spectrum of flight/ground loads.

Determination of Life Limits and Inspection Intervals

A Flaw Tolerant fatigue test program should include three types of specimens. At least one "as-manufactured" specimen is needed to establish a baseline of strength and to correlate with design analysis. Multiple specimens with barely detectable flaws in critical areas are then tested to determine an overall retirement time. At least one specimen with clearly detectable flaws in critical areas is used to determine inspection intervals. It should not be necessary to provide new specimens for each phase of this program, since runouts (non-fractures) is a likely result from the as-manufactured specimen, and possibly from the barely detectable flaw specimens. Flaws can be added to these runout specimens and used in the next phase of the program. The testing itself is conventional accelerated load S-N testing with crack detection by the best laboratory means available. Multiple load path specimens can have the first load path failed "naturally" as a consequence of the S-N testing, or "artificially" by sawcutting, removing fasteners, or otherwise disabling a load path.

For both single load path and multiple load path structure, the retirement time is based on the assumption that barely detectable flaws are present in the structure at all critical locations. The inspection interval for single load path structure is based on the assumption that clearly detectable flaws are present in the structure at all critical locations. The inspection interval for multiple load path structure is based on the life of the second load path, with barely detectable flaws in all critical locations, following complete fracture or disabling of the first load path. No assumption needs to be made as to the cause of failure of the first load path, however, limit load capability should be verified with the one load path failed or disabled.

Determination of retirement times and inspection intervals is done by conventional safe-life calculations using the flawed mean strengths demonstrated by test and/or analysis. Working curve reductions may be smaller than for the conventional calculation, typically "2-sigma" instead of the conventional "3-sigma". Using the conventional reductions would essentially be an assumption that every component in service had the maximum flaw in every critical location for its entire lifetime - an excessively conservative assumption. The flight loads, usage spectrum, cycle counts, prorates, and damage calculation methodology used should be the same for each calculation. Multiple load path inspection interval calculations should include a correction for damage that may occur in the second load path in the time before the first load path is completely severed.

A retirement time should also be calculated using the strength of the as-manufactured specimen and conventional working curve reductions. This should be compared with the retirement time for the barely detectable flaw specimens with the reduced working curve reductions. The lower of the two results is used to retire the part.

Inspections on Flaw Tolerant parts are for the presence of the flaw, not a crack. If the flaw is not found, the part may be returned to service for another inspection interval, up to the overall retirement time of the part. If the flaw is found, the part is retired, or, if a repair procedure has been qualified and approved, repaired and returned to service for another inspection interval, up to the overall retirement time of the part.

EXAMPLES OF FLAW TOLERANT SUBSTANTIATIONS

CH-53A/D Horizontal Hinge Pin

An out-of -production U.S. Navy helicopter was evaluated to determine what actions were required to extend its service life considering the effects of known degrading conditions occurring on the dynamic components. The method selected was: first, an engineering evaluation of each component's sensitivity to known degrading conditions; second, coupon testing to determine potential strength reductions from the various types of selected degrading conditions; and third, application of these reductions to existing full-scale fatigue data from conforming parts. Actions were formulated using conventional damage calculations based on the reduced full-scale strength.

One of the evaluated components was the main rotor head horizontal hinge pin, a 4340 steel component that was subject to corrosion in service. Coupon testing with various degrees of corrosion indicated a significant reduction in strength - up to 63% for "worst case" corrosion pitting. Figure 3 illustrates the penalty for this effect considered as a further-reduced working curve. A "life" of 1500 flight hours results from using this curve and the standard damage calculation for this model helicopter. The action recommended for this component was to inspect for corrosion at the scheduled overhaul every 1200 hours. Corroded parts are rejected, clean parts are returned to service for another overhaul interval, up to their normal 8300-hour retirement time.

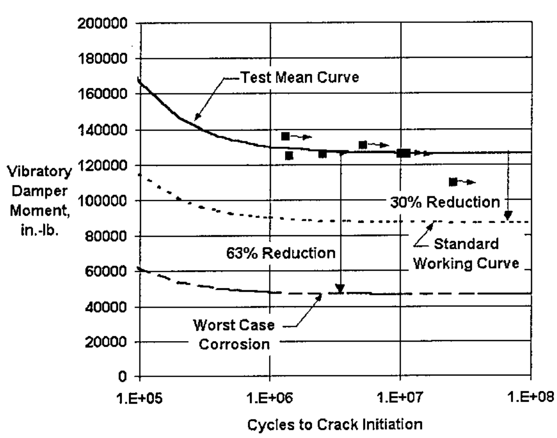

Figure 3. Effect of Corrosion on Hinge Pin

This example is very nearly the Flaw Tolerant methodology recommended above, except that full-scale tests with flaws are not conducted. The working curve is set at the maximum reduction for corrosion, rather than reducing the mean by the average effect of the flaw and then taking a further 2-sigma reduction. The two approaches would produce similar results.

The inspection for corrosion is easy, and may be conducted at the time of overhaul when the component is disassembled.

S-76 Tail Rotor Pitch Horn

Corrosion was discovered on some in-service tail rotor pitch horns at in the critical fatigue site for the safe-life substantiation. These horns are aluminum and have a conventional safe life of 22,000 hours. A full-scale fatigue test program was conducted which included horns with the worst service-related corrosion, and horns subjected to a severe salt fog chamber exposure.

Results of the full-scale program are shown in figure 4. The effect of corrosion is much smaller in this case, although there is a high scatter when the conservative salt fog chamber results are included. A standard working curve is used in this case, in order to capture the lowest corroded data point. The life calculation for this working curve produces a 12,000 hour result. The retirement time for all S-76 tail rotor horns was changed to this value.

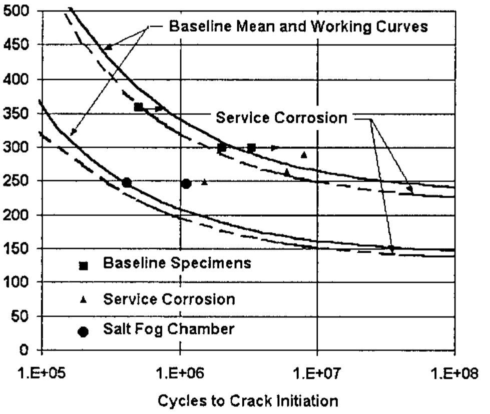

Figure 4. Effect of Corrosion on Pitch Horn.

As a Flaw Tolerant substantiation, this example contains the elements of full-scale test with flaws, and worst case flaws imposed by a conservative but somewhat artificial means. Imposing a retirement time instead of an inspection option is due to the fact that almost every horn will have some degree of corrosion at 12,000 hours anyway, and a rework procedure was not substantiated.

SH-60B Horizontal Stabilizer

This component was substantiated in fatigue as if it were a dynamic component, in spite of its "airframe" design features. Full-scale fatigue testing of the prototype configuration revealed two cracking modes - in the web of the forward spar of the right-hand wing panel, and in the aft attachment fitting of the center box structure. These cracks were several inches long and stopped by reaching a joint or edge. The conventional safe lives for these modes were low and a redesign was initiated. However, an interim position was needed to allow the program to continue until the redesign was available. The method chosen was to conduct "crack re-initiation" testing of the unit it its cracked condition. 250 hours of testing was accomplished on the wing panel and 160 hours on the center box at conservative loads without the initiation of any additional cracks. A visual inspection for the original cracks was added to the daily walkaround inspection. The cracks were easy to find visually and the inspection did not require any disassembly.

This is an example of a multiple load path Flaw Tolerant substantiation. The first load path failures are the initial cracks, which were not propagating further. A good crack re-initiation interval was demonstrated for the remaining load paths, albeit without an S-N curve and rigorous methodology, allowing an easy inspection to be conducted at a short interval (daily). If the initial cracks were found, the part would be removed from service.

SH-60B Servo Beam Rails

These four components provide the mounting hardpoints for the three horizontally mounted main rotor servocylinders on the SH-60B, each one mounted to two rails, two feet on each. Barrel nuts in each rail lug receive the servo mounting bolts. The conventional S-N testing on the rails showed fretting fatigue origins in the barrel nut holes, yielding calculated safe-lives of 4000 to 5000 hours. An evaluation of fail-safety was then conducted by continuing the testing until an additional crack initiation was noted, usually at a different location in the same barrel nut hole. The two crack re-initiation results for one of the rail types are shown in Figure 5. The "life" calculation, conservatively using a conventional "3-sigma" working curve, produced a 2900-hour result. This result was proposed to be used to justify a phase inspection for the initial cracks at 300 hours. No disassembly is required, and the initial cracks are easily seen in a visual inspection.

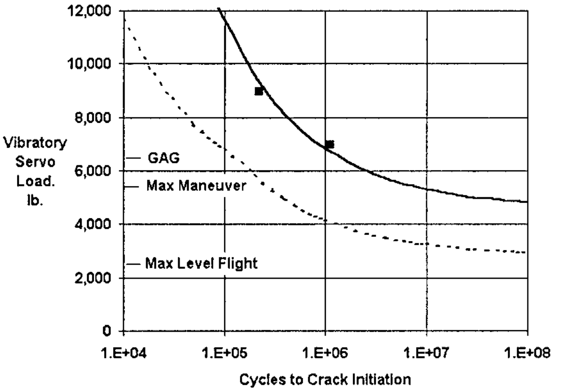

Figure 5. Crack Re-Initiation on Servo Beam Rail

S-92 Main Rotor Hub

Most of the S-92 dynamic components have been initially selected for a Flaw Tolerant substantiation. The main rotor hub is the largest and most complex of these - a titanium forging, machined all over, and designed for easy inspections, Figure 6. At the time of this writing the first, as-manufactured, full-scale fatigue specimen testing has been completed, but none of the flawed specimens have been tested. The result for the first hub specimen was a runout (non-fracture), because of the inability to increase the test load beyond the hub's geometric flapping limits. Strain surveys indicated that the hub was operating in the test at about half the conservative design fatigue allowable for the material.

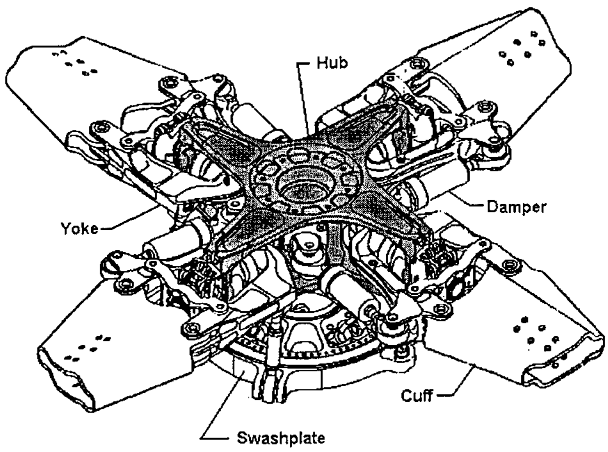

Figure 6. S-92 Main Rotor Head

Even though the strength of the flawed full-scale hub is not available, the results of a Flaw Tolerant substantiation can be estimated. A coupon program evaluating the effects of various types of flaws indicates which type is most critical and provides a conservative estimate of the strength-reducing effect. A study of fielded Sikorsky components indicated that an .040" deep flaw was possible on titanium, and this was selected as the Clearly Detectable Flaw size. The Barely Detectable Flaw was selected as .005" deep based on the easily-seen appearance of a flaw of this depth on the titanium coupons with the as-manufactured surface finish. The coupon results showed little or no effect of the Barely Detectable Flaws - scratches, indents, or gouges. However, the Clearly Detectable Flaw study showed a fatigue strength reduction of up to 57%, the worst being an .040" deep gouge, Figure 7.

Figure 8 illustrates how the Flaw Tolerance substantiation should look. The runout full-scale test result is doubled in strength based on the strain survey, providing an estimate of the actual as-manufactured hub strength. This curve is then reduced by 57% to account for the potential effect of .040" gouges in critical sections. A further reduction of 20% (2-sigma) is added to produce a working curve for the flawed strength. A "life" calculation with this working curve, predicted flight loads, and the commercial usage spectrum produces a 15,000-hour result. This figure could be used as an inspection interval, inspecting for the presence of the flaws. In practice, the inspection would likely be done at the time of a major inspection interval, such as 1250 hours.

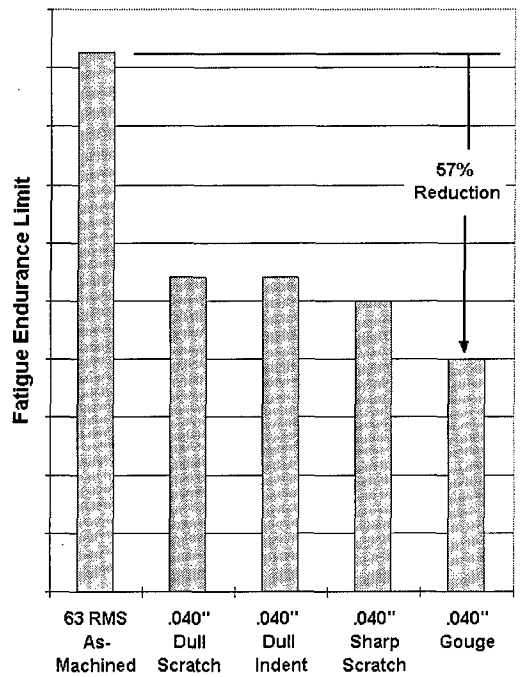

Figure 7. Coupon Evaluation of Flaws on Titanium

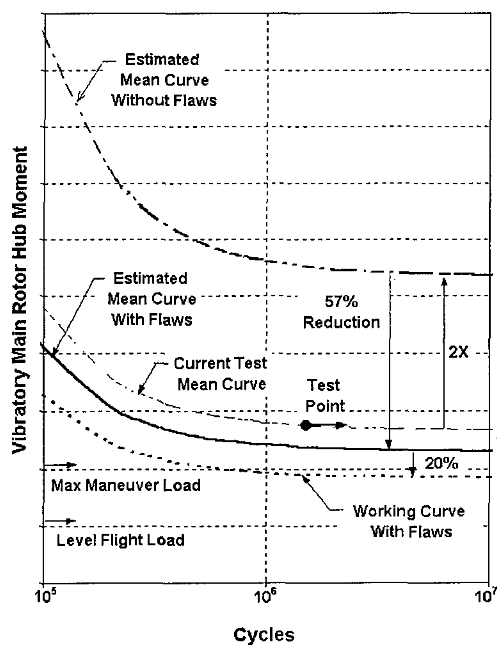

Figure 8. Flaw Tolerance Evaluation of S-92 Hub.

COMPARISON OF METHODS

Having the Flaw Tolerant method available provides an additional capability to successfully achieve the design goals of a helicopter project. Table 1 illustrates the pros and cons of the choice of method for single load path metal structure. The Damage Tolerance approach for helicopters has been shown as both the "No/Benign Crack Growth" method and the "Slow Crack Growth" method. These methods are also described as "Damage Tolerance Without Inspection", and "Damage Tolerance With Inspection", respectively.

The Slow Crack Growth method of Damage Tolerance provides the significant advantage that it does not matter what the original source or cause of the cracking is (up to the point where the initial crack size is bigger than the minimum inspectable size). So flaws and defects of different character, size, or location than anticipated would still be accommodated by the substantiation. However, as discussed in Reference 5, every inspection method and interval must be compatible with the missions, limitations, and economics of helicopter operations worldwide. This is the critical difficulty in applying Slow Growth Damage Tolerance to helicopter dynamic components. Improvements in analytical methods, design concepts, materials, and NDI methods are needed to make it practical to confidently apply this method more frequently than we can today.

Both the No/Benign Crack Growth method and the Flaw Tolerant method require some degree of a priori research and decisioning on the types and severities of flaws and defects that will be considered in the substantiation. However, currently these methods offer the telling advantage of being practical to the operator - the No/Benign Crack Growth method requiring no inspections, the Flaw Tolerant method only requiring inspections for significant flaws, at reasonably long intervals. All three methods (Flaw Tolerance, Slow Crack Growth, No/Benign Growth) provide retirement times much higher than frequently achieved today by conventional safe life.

Change in the original substantiation assumptions of a new model helicopter are inevitable, and have differing effects on the structural substantiation methods. In the case of the No/Benign Growth method and the Flaw Tolerant method, initial assumptions must be made with respect to the initial level and location of damage. If these assumptions are not well-founded and sufficiently conservative, new levels, types, or locations of damage which occur during the service life of the component may require a resubstantiation involving new tests and/or analysis. In the case of the Slow Growth Damage Tolerance method, this event is much less likely.

The most likely change to occur is an increase in loads. "Mission creep", configuration changes, higher gross weights,

Table 1.
Pros and Cons of Method Choice
Single Load Path Metal Components

Method	Recurring Inspection Required	Initial Damage Assumption	Consequence of Increased Initial Damage Assumption	Consequence of Increased Load or Spectrum	Principal Design/Application Issue
No/Benign Crack Growth Dam. Tol.	None	Evaluation of Manufacturing and Service Defects	New Analysis/Test, New Life Limit	New Analysis/Test, New Life Limit	Defining/Using Initial Crack Size
Slow Crack Growth Dam. Tol.	Inspect for Cracks	None Required	No Change	New Analysis/Test, New Insp. Interval	Achieving Practical Insp. Method and Interval
Flaw Tolerance	Inspect for Flaws	Evaluation of Manufacturing and Service Defects	New Analysis/Test, New Life Limit or Insp. Interval	New (Simple) Analysis, New Life Limit or Insp. Interval	Defining and Applying Flaws

and more powerful engines are all part of the growth and evolution of a helicopter model, and all contribute to higher loads in the dynamic components. All three of the methods can accommodate these changes, by reducing life limits and/or inspection intervals as needed. The basis for the change in the Damage Tolerance methods is a new fracture mechanics analysis and/or test program incorporating the higher loads. Flaw Tolerance on the other hand, can accommodate higher loads by a simple modification to the existing damage calculation.

The above discussion is appropriate only if all of the methods are valid and well founded. The critics of the Flaw Tolerant method argue that it is entirely empirical and not based in any scientific principal of damage accumulation. Advocates argue that Flaw Tolerance is a proven methodology and does offer a significant improvement over conventional safe life, even if it is empirical. Then, given that it is currently impractical to apply Damage Tolerance to every possible fatigue mode on every helicopter component, we need to be able to continue to take advantage of the benefits of the Flaw Tolerant methodology.

CONCLUSIONS

1. Helicopter fatigue substantiations can be and should be significantly improved by the consideration of flaws and defects.

2. Damage Tolerance offers promise to provide this improvement but currently cannot be economically applied to every fatigue mode on every helicopter dynamic component.

3. Flaw Tolerance can achieve the desired improvement using methods that are available and proven effective, and can do so within reasonable cost, weight, and maintainability constraints.

4. Flaw Tolerance should continue to be an equal-choice method for civil helicopter fatigue substantiations, and considered as a practical alternate to Damage Tolerance in military substantiations.

ACKNOWLEDGMENTS

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REFERENCES

1. Regulation - Federal Aviation Administration Airworthiness Standards: Transport Category Rotorcraft, Paragraph FAR 29.571, "Fatigue Evaluation of Structure".
2. Advisory Circular - Federal Aviation Administration Advisory Circular AC 29-2A, Appendix 1, "Fatigue Evaluation of Transport Category Rotorcraft Structure (Including Flaw Tolerance)".
3. Technical Paper - "Rotorcraft Fatigue and Damage Tolerance", W. Dickson, J. Roesch, D.O. Adams, B. Krasnowski, Prepared for the Technical Oversight Group on Aging Aircraft (TOGAA), January 1999 (unpublished at the time of this meeting, copies available from D.O. Adams).
4. Technical Paper - "Methodology for Fatigue Substantiation of Alternate Sources and Degraded Modes on Helicopter Dynamic Components", D.O. Adams, C. Albrecht, W.D. Harris, 44th Annual Forum of the American Helicopter Society, Washington DC, June 1988.
5. Technical Paper - "Damage Tolerance Applied on Metallic Components", T. Marquet, A. Struzik, 24th European Rotorcraft Forum, Marseilles, France, September 1998.